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# Accepted manuscript

## Macroecological inferences on soil fauna through comparative niche modeling: the case of Hormogastridae (Annelida, Oligochaeta)

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# Macroecological inferences on soil fauna through comparative niche modeling: the case of Hormogastridae (Annelida, Oligochaeta)

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## Abstract

Ecological Niche Modeling (ENM) through MaxEnt and quantitative comparison techniques using ENMtools could facilitate ecological inferences in problematic soil dwelling taxa. Despite its ecological relevance in the Western Mediterranean basin, the ecology of the endemic family Hormogastridae (Annelida, Oligochaeta) is poorly known. Applying this comparative approach to the main clades of Hormogastridae would allow a better understanding of their ecological preferences and differences. One hundred twenty-four occurrence data belonging to four clades within this earthworm family were used as input to infer separate MaxEnt models, including seven predictor variables. Niche breadth, niche overlap and identity tests were calculated in ENMtools; a spatial Principal Components Analysis (sPCA) was performed to contrast with the realized niches. The highly suitable predicted ranges varied in their ability to reflect the known distribution of the clades. The different analyses pointed towards different ecological preferences and significant ecological divergence in the four above-mentioned clades. These results are an example of wide-scale ecological inferences for soil fauna made possible by this promising methodology, and show how ecological characterization of relevant taxonomic units could be a useful support for systematic revisions.

**Keywords:** Ecological niche models, ENMtools, macroecological inferences, soil fauna, Hormogastridae

Abbreviations:

ENM - Ecological Niche Modeling

sPCA – Spatial Principal Component Analysis

ROC-AUC - Receiver Operating Characteristic- Area Under the Curve; AUC in shorter form

TRANGE - Mean Diurnal Range

ISOTHER - Isothermality

TCOLD - Mean Temperature of the Coldest Quarter

PRDRY - Precipitation of Driest Month

LITHO - Lithology

VEGET - Land cover

ANTHRO - Human influence

HGI - Highest gain in isolation

HDGO - Highest decrease in gain when omitted

## 1. Introduction

Macroecological studies comparing the ecological preferences of different soil taxa are almost absent from the literature (but see [1]): this is not necessarily a case of a lack of

interest for this community, but most probably related to the difficulty of their study [2].

One approach which has facilitated the ecological inferences in these problematic groups is Ecological Niche Modeling (ENM), with MaxEnt [3] standing out among the different methodologies due to its high performance when including presence data only. It has been implemented in several groups (ground beetles [4], termites [5], millipedes [6]) including earthworms: [7] used MaxEnt to study the effect of large-scale ecological variables in the distribution of *Hormogaster elisae*, corroborating its high predictive power and the ability to reflect accurately its soil preferences.

Additionally, the implementation of several existing indices and statistical tests in the software ENMtools [8] has allowed the quantitative comparison of Ecological Niche Models (ENMs) between related species, including niche overlap, niche breadth and testing for statistically significant differentiation. Some recent studies have proven the usefulness of these methodologies to answer diverse biological questions, applying them to different animal groups. For example, [9] found ecological niche differentiation in two cryptic beetle species, using the fact as support for their status as valid species. [10] studied niche overlap and niche breadth in three cryptic bat species complexes, as part of their research on how environmental factors and ecological interactions influenced their speciation. However, these promising and insightful methodologies have been scarcely used to address similar questions in soil animals (and especially earthworms).

Several authors have justified the utility of both modelling distributional patterns and ecological niche characteristics above the species level (e.g., [11,12,13]) when individual species have scarce occurrence data.

This approach appears promising for a relatively obscure earthworm family, the Hormogastridae Michaelsen 1900. It is the second most diverse earthworm family in the western Palearctic region, after the Lumbricidae Claus 1876. They play an important ecological role as deep-burrowing endogeics in the western Mediterranean basin [14], processing great amounts of soils expelled as casts [15]. In some places, such as Sardinia, they were shown to be dominant in abundance in earthworm communities [16], being adapted to drought and impoverished soils [17,18]. To understand better the role of hormogastrids in soil ecosystems, it is necessary to comprehend their ecological preferences, adaptations and response to environmental variables. However, those have been scarcely studied, mainly focusing on one particular species: *Hormogaster elisae* Álvarez 1977. The larger body size and associated slower reproductive rate [19] of most species in the family, together with their scattered distribution and difficult capture (their deep burrowing requires intensive digging efforts), have discouraged their laboratory and field research. The only work on their ecological preferences [20] corroborated the presence of most hormogastrids in soils with low nutrients content, with a preference for soils more basic and fine-textured than the ones observed for *H. elisae*.

The phylogeny of Hormogastridae has been clarified in the last years using molecular evidence: after [21,22,23] it has been divided in 9 clades. *Xana*, *Vignysa*, *Hemigastrodrilus* and *Ailoscolex* had already been described as independent genus, but

the other five remain artificially joined in the catch-all genus *Hormogaster*. Four of these latter clades (informally termed Central Iberian, Northeastern Iberian, Tyrrhenian, and Disjunct) have wide geographic ranges and a high number of known populations, which makes them suitable for an in-depth macroecological study. Understanding their ecological preferences and the differences in their ecological niches would be helpful as an additional support for their future definition as new genera in the taxonomic revision of the family.

The main aim of this work is to obtain macroecological inferences for the four main clades of *Hormogaster* through comparative niche modeling as an example of the potential of this methodology. We used all the available geo-referenced presence locations to obtain the ENMs for each of the clades, and ENMtools and niche space visualization to perform quantitative comparisons. Our objectives were: i) to predict the distribution of the main clades of *Hormogaster* in their home range; ii) to find the environmental variables with a stronger influence in their distribution; iii) to study the overlap, breadth and statistical differentiation of their ecological niches; and iv) to compare their potential and realized niches.

This study could be potentially useful as a base for wide-scale ecological inferences in other groups of earthworms and soil fauna, a key element on most ecosystems around the world.

## 2. Materials and methods

### 2.1. Training data



One hundred twenty-four presence localities were used to train the models (detailed in Suppl. Material 1): 44 for the Central Iberia clade, 29 for the Tyrrhenian clade, 30 for the Northeastern Iberia clade and 21 for the Disjunct clade. All the presence data were obtained in sampling campaigns by the authors, ensuring high reliability; they also constitute a good representation of the known ranges of the species, defined after more than a century of field works by other researchers in the Mediterranean.

The Central Iberia clade corresponds to the *H. elisae* morphospecies, which comprises at least five cryptic lineages [24]. [7] included several new populations, which considerably widened its known range; their genetic variability is currently being researched.

The Northeastern Iberia clade comprises a high number of closely related species (see Suppl. Material 1) with high morphological variability in their diagnostic characters [20]. They inhabit Northeastern Spain and a small region of Southeastern France, with most of their diversity located in Catalonia (Spain).

The Disjunct clade includes the Sardinian populations of *H. pretiosa* Michaelsen 1889 (a taxonomically problematic species into which other unrelated species were wrongfully assigned [21]) confined to the southwestern part of the island, *H. najaformis* Qiu & Bouché 1998 and *H. regina* Rota 2016 from Catalonia (Spain) and an assembly of undescribed related forms in the latter region.

The Tyrrhenian clade includes *H. redii* Rosa, 1887, *H. samnitica* Cognetti, 1914 and their subspecies. [25] found deep genetic divergence pointing to them being composed of cryptic lineages. They are distributed around the Tyrrhenian Sea, occupying most of Sardinia, Corsica, Tuscan Archipelago, the Tyrrhenian side of Italy

from Tuscany to Naples, Sicily and a small area between northern Algeria and Tunisia [16].

## 2.2. Environmental variables

The large-scale variables potentially relevant for the biology of Hormogastridae were chosen as predictor variables to model its distribution, as described below.

Four bioclimatic variables were selected from Worldclim (<http://www.worldclim.org/> accessed 12/05/2016): Mean Diurnal Range-BIO2 (**TRANGE**) and Isothermality-BIO 3 (**ISOTHER**) are suitable to represent the influence of extreme temperature variation (both daily and across the year) on earthworm distribution in the Mediterranean region. Mean Temperature of the Coldest Quarter-BIO11 (**TCOLD**) was chosen to reflect the impact of soil freezing and low temperatures on the activity of earthworms. Precipitation of Driest Month-BIO 14 (**PRDRY**) is likely to reflect the availability of water in the soil across the year (an essential requirement for earthworms) and the severity of drought periods.

As topographical variable we selected Lithology -PAR-MAT-DOM2, Second level code for the dominant parent material of the STU from the European Soil Database Raster Library 1kmx1km ([http://eusoils.jrc.ec.europa.eu/ESDB\\_Archive/ESDB\\_data\\_1k\\_raster\\_intro/ESDB\\_1k\\_raster\\_data\\_intro.html](http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB_data_1k_raster_intro/ESDB_1k_raster_data_intro.html) accessed 12/05/2016)- (**LITHO**). Lithology is likely to influence indirectly Hormogastridae ecology through a wide range of correlated variables, including the structure and biochemical characteristics of soils.

CORINE 2006 Land Cover (version 12/2009: <http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-clc2006-100-m-version-12-2009> accessed

[12/05/2016](#)) – (**VEGET**) was chosen to incorporate information about vegetation and land use, which are widely known to influence earthworm distribution (e.g. [26]).

As large, deep burrowing species as most Hormogastridae are affected negatively by human disturbance [27], the ‘Human footprint’ data set -representing the human influence on land surface [28] - (**ANTHRO**) was selected to include the effect of anthropic activities on habitat suitability.

These variables were the same that successfully predicted the distribution of *H. elisae* (and relevant soil characteristics) in [7]. Precipitation of the coldest quarter was replaced by Mean Temperature of the Coldest Quarter to represent the inactivity period in the coldest months.

After testing for collinearity, no significant correlation above 0.8 was found between the predictor variables, thus none was removed.

### **2.3. Ecological niche modeling**

The following parameters of the model as implemented in MaxEnt were considered by default: a maximum number of 500 iterations, a convergence-threshold limit of 0.00001, 10,000 points as number maximum of background points and regularization multiplier equal to 1, as recommended by [3]. Background points were randomly selected from the home range of the family: Iberian Peninsula, Southern France, Corsica, Sardinia, Italy and Sicily. Northern Africa was not included due to the lack of data for some variables. Due to the gaps in the knowledge of earthworm fine-scale distribution, sampling bias and dispersal ability we chose the background point selection method which requires fewer assumptions over other more restrictive approaches.

Ten replicates were run for each model. Each time, a 30% of the sample records were randomly removed without replacement (through the subsample option) to be used as test points in order to measure the quality of the model, and the 70% of records were used to build the model (e.g. [29]). The final model was constructed with the average of the replicates.

The ROC-AUC (Receiver Operating Characteristic- Area Under the Curve) technique has been implemented in MaxEnt to analyze the goodness of fit of the analysis in contrast to other models of evaluation, since it avoids the problem of selecting threshold values [30]. It is capable of measuring the model ability to discriminate between the sites of species presence from the areas of absence [31,32,33,34].

## 2.4. Niche analysis

The statistics **niche overlap** [35] –which reflects the similarity between the niche models- and **niche breadth** [36] were calculated using ENMTools 1.3.

**Niche overlap** analyses were applied to pairwise comparisons of all clades, based on the values of two indexes, Schoener's  $D$  [37] and Hellinger's  $I$  [35]. Low values of these statistics indicate little overlap, while values close to 1 mean great similarity.

Levin's  $B1$  (inverse concentration) and  $B2$  (uncertainty) [38] were obtained for each clade as a measure of **niche breadth**: higher values of these indexes indicate a broader niche.

The **identity test** (or test of niche equivalency) was run in ENMtools to test for statistically significant differences between the obtained ENMs. A null distribution is

produced by pooling together all occurrence data from two clades and randomly separating them in two sets, generating two ENMs and obtaining their overlap values (with 100 separate replicates). If the observed  $D$  and  $I$  overlap values are lower than the confidence interval of the null distribution, the null hypothesis of both niches being equivalent is rejected.

We decided not to employ the background test (or test of niche similarity), which relies in the *a priori* definition of the available space for the different studied clades. According to [8] the delimitation of the available background is a critical aspect of the test, and we lacked enough biological or geographical justifications to define it with confidence.

## 2.5. Realized niche visualization

Spatial principal components analysis (sPCA) was used following [10] to visualize the ecological niches of the different clades. The values of all the environmental variables were extracted for each presence record, and a PCA was performed in STATISTICA 7 (StatSoft Inc, Tulsa, OK, USA). The resulting factor scores for each record were imported into ArcGIS 10.0 as x, y coordinates. Minimum convex polygons were drawn to delimit each clade's realized niche (the actually occupied environmental space) and their individual areas and the area of overlap between the niches were measured.

## 3. Results

### 3.1. Ecological niche models

All models showed high predictive power, with good to very good average AUC values [39]: Tyrrhenian 0.951, Central Iberia 0.990, Northeastern Iberia 0.856, Disjunct 0.960.

The geographical representation of the predicted suitability values is shown in figure 1. The predicted highly suitable areas roughly matched the known extent of their ranges for the Central and Northeastern Iberia clades; for the Disjunct and Tyrrhenian clades the areas were respectively wider and narrower than expected according to literature [16]. A few isolated areas outside the known range of Hormogastridae were also predicted as highly suitable.

The relative contributions of the variables to each model are shown in figure 2; the variables with highest relative contribution, highest gain in isolation-HGI (the one which improves the model the most when the rest are removed) and highest decrease in gain when omitted-HDGO (the one which worsen the model the most when removed) for each model are shown in table 1. The preferred classes for the two categorical variables (lithology-LITHO and land cover-VEGET) are shown in table 2. In all of these cases important differences were found between the clades.

Figure 1

Figure 2.

Table 1.

Table 2.

### 3.2. Niche analysis

The Northeastern Iberia clade showed the broadest niche (indicated by the highest value of B1 and B2: 0.36 and 0.95 respectively), while the Central Iberia clade showed the narrowest (B1 and B2: 0.03 and 0.79). The most similar niches were Tyrrhenian and Disjunct, which is indicated by the highest values of niche overlap (I: 0.85, D: 0.60).

Northeastern Iberia was more similar to them ( $I$ : 0.50-0.70,  $D$ : 0.24-0.42) than Central Iberia, which showed the lowest overlap with the rest ( $I$ : 0.14-0.25,  $D$ : 0.04-0.08).

The Identity test (or test of niche equivalency) showed significant differences between all the niches by rejecting the null hypothesis of niche identity with very high confidence ( $\alpha=0.01$ ) both for  $I$  and  $D$  statistics.

### 3.3. Realized niche analysis

The first two PCA factors chosen for the realized niche representation explained 55,21% of the variance. The first factor was highly and positively correlated to Mean Temperature of the Coldest Quarter-(TCOLD). Isothermality (ISOTHER) and Mean Diurnal Range (TRANGE) were negatively correlated to the second factor.

The Central Iberia niche is highly divergent from the Tyrrhenian and Disjunct niches, which in turn are spatially close (and show high mutual overlap percentages). The Northeastern Iberia niche, with the largest area, widely overlaps with the other three niches, with the highest percentages corresponding to Central Iberia and Tyrrhenian niches (figure 3).

Figure 3.

## 4. Discussion

### 4.1. Predicted suitable ranges

While the habitat suitability predictions mostly adjusted to our knowledge of hormogastrid earthworm distribution, some highly suitable areas were highlighted

where they have never been found after intensive sampling (but being deep burrowers with a patchy distribution leaves the possibility of false negatives [7]). According to [36], absence from some part of the predicted niche suggest the action of unidentified factors excluding the species from these locations, such as competition or dispersal limitation. A combination of paleogeographical events [16,21,26] and competition [40] with other earthworms (mainly the family Lumbricidae) could explain some of the most remarkable absences. The Northeastern Iberia clade has not been found in the highly suitable zone of Cantabria and the Basque Country: this region was covered by the sea until the Upper Tertiary, then it was likely colonized from Aquitaine (France) by its dominant lumbricid fauna, with *Lumbricus friendi* and the giant *Scherotheca* sp among them [41]. Something similar could explain the absence of the Disjunct clade in the Balearic Islands. All their area except the main mountain ranges in Majorca got submersed during episodes in the Oligocene and Miocene, and the available environment was likely already inhabited by another big-sized endogeic lumbricid genus, *Postandrilus* sp. [42,43,44].

Other highly suitable areas in Galicia, Portugal and Andalucía are too far from the main range of Hormogastridae to have been colonized during its evolutionary history. It is well known that endogeic earthworms have poor active dispersal capabilities, as [45] found for *H. elisae*, which hardly moves to find a mating partner. Passive dispersal is still possible for earthworms, so geographical barriers or extinctions through their long evolutionary history could also explain their absence.

A specific case of this overprediction was the Disjunct clade predicted suitable range, which was wider than expected. These earthworms are absent from Northern Sardinia,



Corsica, the Tuscan Archipelago, continental Italy and Sicily (thoroughly sampled areas as reviewed by [16]), but a few highly suitable areas were found in them. Competitive exclusion from suitable habitats by the overlapping Tyrrhenian clade seems unlikely, as they have been found in sympatry (showing vertical niche segregation with *H. redii* in Sardinian localities –*pers. obs.*). One possible reason for this phenomenon is the important influence of tectonic events in the dispersion of these animals [25,46]: the absence of the Disjunct clade from the microplates that drifted eastwards would explain their absence from areas that the Tyrrhenian clade managed to reach.

The other main finding was the inferior fitting of the predicted suitable range of the Tyrrhenian clade to our previous knowledge. [16] found a strong presence of *H. redii* and *H. samnitica* in continental Italy, while our model showed few highly suitable areas. The low predictive performance could be explained by the scarce number of Italian occurrences included in the training data despite the strong sampling effort.

Overall, our results confirmed the suitability of ecological niche modeling at above-species level for soil-dwelling fauna, as seen in [47]; but also highlighted the importance of comprehensive sampling through the known range, and the influence of the specific characteristics of the clades in its performance.

#### **4.2. Ecological characterization and niche differentiation**

The differences in the most relevant environmental variables for each clade hint at differential ecological preferences (as seen in [36]). Precipitation showed a strong

influence on Tyrrhenian, Northeastern and Central Iberia clades but their response differed (as shown by response curves, Suppl. Material 2): the Tyrrhenian clade showed a preference for the driest climate, Northeastern Iberia showing increased probability of presence in wetter habitats and the Central Iberia earthworms in between.

Meanwhile, low temperature affected Disjunct clade distribution significantly. There is some empirical evidence for the differential effect of these variables. For example, earthworms of Northeastern Iberia and Disjunct clades have been found in the same location in a humid but cold month; the former were active but the latter were aestivating. Conversely, Disjunct clade earthworms were found active in drier soils under warmer conditions (*pers. obs.*).

Even when its influence was moderate compared to climatic variables, the clades showed different responses to human influence, with the Central Iberia and Disjunct clades being the most affected.

Land cover heavily influenced the Northeastern Iberia clade, as lithology did for them and the Disjunct clade. The preferred land uses and lithological classes found for the four clades constitute a useful preliminary description of the habitats these earthworms select.

While it can be argued that small scale soil variables should be considered to study the ecological preferences and differences between these soil-dwelling taxa, to our knowledge this is not a concern. On one hand [7] showed strong correlation between large-scale environmental variables and the most relevant soil variables affecting *H. elisae* distribution: this supports our studied variables covering to some extent the

variability of lower-scale variables. On the other hand, preference for local soil conditions should be expected to be less conserved across clades than large-scale environmental variables, thus being less suitable for macroecological analysis at above-species level.

Together with the significant differences between the ecological niches shown by the identity test, these results highlight the ecological divergence between the studied clades; in a similar way [47] highlighted the ecological divergence of the four main clades of the soil-dwelling mite harvestmen (Cyphophthalmi). It does not only reinforce their biological relevance as evolutionary entities; it also provides additional characters to the diagnosis of the future generic system in Hormogastridae: altitudinal preference, selected habitats and lithologies, and susceptibility to drought and cold periods being the most remarkable.

According to the niche conservatism hypothesis, higher niche similarity should point to closer phylogenetic affinities between the clades. Interestingly, Tyrrhenian and Disjunct have been hypothesized to be sister clades based on morphology (sharing multiple spermathecae) and phylogenomic analysis [22]. Unfortunately, the scarce occurrence data for individual species of Hormogastridae hinders any attempt of correlating niche similarity and phylogenetic relatedness at a finer scale, but it could be more easily implemented to other groups of soil fauna with more widespread species.

#### **4.3. Niche breadth and overlap: predicted vs realized niche**

The predictions of niche breadth from Levin's index and sPCA areas were in agreement. This suggests there is a good correspondence between the predicted and realized niches of the four clades.

It is worth noting that field observations indicate *H. redii* has an exceptionally wide ecological valence [16], which was not reflected in a highest niche breadth of its (Tyrrhenian) clade. This indicate analyzing above-species level clades could sometimes mask the ecological particularities of some of their members.

The high overlap between Tyrrhenian and Disjunct realized niches is concordant with the overlap shown by *D* and *I* indexes. The high overlap between Northeastern Iberia and the other realized niches is also in agreement with these indexes, except for Northeastern-Central, which is surprisingly lower according to the latter.

These results show sPCA as a valuable complementary analysis in ecological niche studies, which provides additional insight in aspects like niche filling.

## 5. Conclusions

MaxEnt allowed predicting with varying accuracy the highly suitable range of the main Hormogastridae clades; some exceptions constitute an interesting starting point for hypothesis on which factors shaped their distribution (dispersal ability, biotic interactions and paleogeographical events among them).

We found evidence for significant divergence in the ecological niches of the studied clades. The analyses also provided information about their differential ecological preferences. In the same way that ecological characters have been proposed to reinforce species delimitation, comparative studies at higher taxonomic levels such as this one appear suitable to characterize and delimit putative genera (or other taxonomic categories).

The Northeastern Iberia clade niche was the broadest, widely overlapping with the rest, while the Tyrrhenian clade was narrower than previously thought. This kind of preliminary results, combined with the reconstruction of the family's divergence, constitute a promising starting point to study their macroecology and macroevolution.

The integration of powerful, objective tools for phylogenetic and macroecological inference will lead to a deeper understanding of the processes operating at wide scale on soil fauna.

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**Tables and headings**

Table 1. Variables with highest relative contribution, highest gain in isolation (HGI) and highest decrease in gain when omitted (HDGO) in the habitat suitability models of each clade. Mean Diurnal Range-(TRANGE), Mean Temperature of the Coldest Quarter-(TCOLD), Precipitation of Driest Month-(PRDRY), Lithology - (LITHO), Land cover-(VEGET).

	<b>Highest contribution</b>	<b>HGI</b>	<b>HDGO</b>
Tyrrhenian	PRDRY (34.4%) TRANGE (27.4%) VEGET (12.7%)	TCOLD	VEGET
Central Iberian	PRDRY (27.8) TRANGE (20.2%) TCOLD (15.9%)	PRDRY	PRDRY
Northeastern Iberian	PRDRY (26.4%) VEGET (25.8%) LITHO (21.6%)	PRDRY	PRDRY
Disjunct	TCOLD (39.2%) TRANGE (23.9%) LITHO (16.6%)	TCOLD	TCOLD

Table 2. Preferred lithologies and land cover classes for the four clades, obtained from the habitat suitability models.

Northeastern Iberian	Lithology	Calcareous rocks, fluvial clays, silts and loams
	Land cover	Permanently irrigated land, vineyards, moors and heatland, transitional woodland-shrub
Disjunct	Lithology	Pyroclastic rocks, acid regional metamorphic rocks, unconsolidated deposits
	Land cover	Permanently irrigated land, vineyards, fruit tree/berry plantations, annual crops associated with permanent crops, land principally occupied by agriculture with significant areas of natural vegetation, and natural grasslands
Tyrrhenian	Lithology	Pyroclastic rocks, acid regional metamorphic rocks, unconsolidated deposits, marine and estuarine clays and silts, residual and redeposited clays from calcareous rocks
	Land cover	Natural grasslands and sclerophyllous vegetation
Central Iberian	Lithology	Consolidated-clastic-sedimentary rocks, arenites and acid to intermediate plutonic rocks
	Land cover	Natural grasslands and sclerophyllous vegetation

### Figure captions

Figure 1. Habitat suitability maps for the four clades in this study. Only values above 0.6 (darker shade) and 0.75 (lighter shade) are shown. The small maps show the occurrence data for each clade, and the colored outline shows the known range of the clade. Central Iberian clade: pink; Northeastern Iberian clade: green; Tyrrhenian clade: red; Disjunct clade: purple.

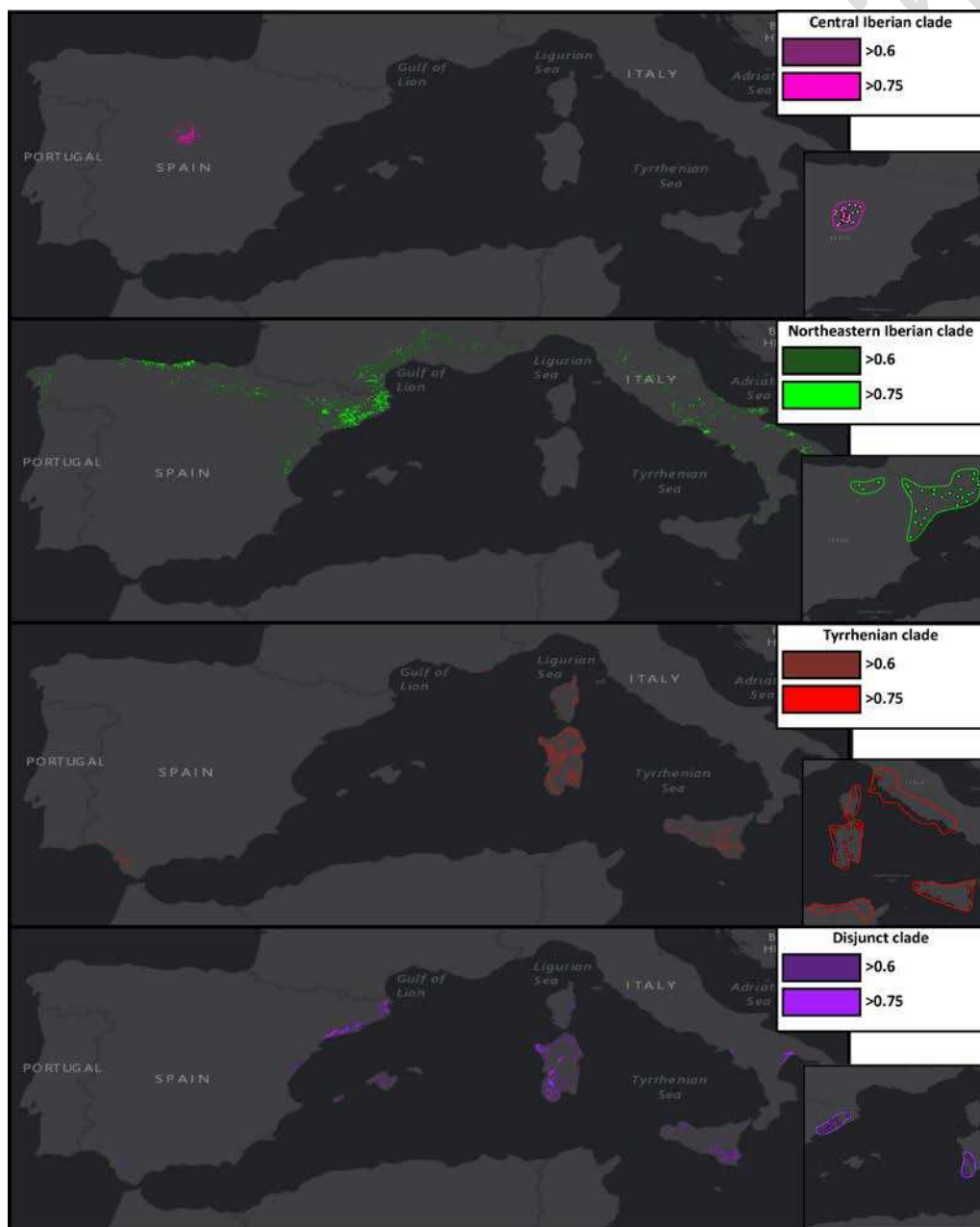


Figure 2. Percent contribution of the environmental variables to the Ecological Niche Models (ENMs). Mean Diurnal Range-(TRANGE), Isothermality-(ISOTHER), Mean Temperature of the Coldest Quarter-(TCOLD), Precipitation of Driest Month-(PRDRY), Lithology - (LITHO), Land cover-(VEGET), Human influence-(ANTHRO).

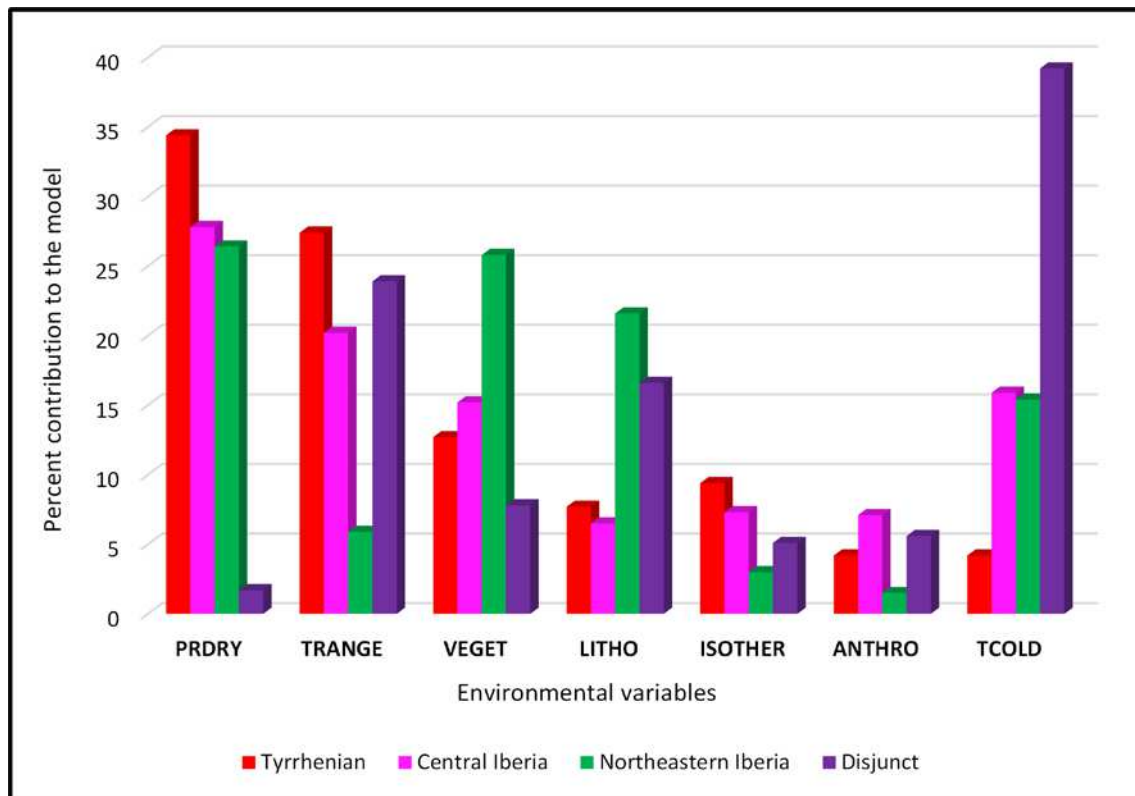
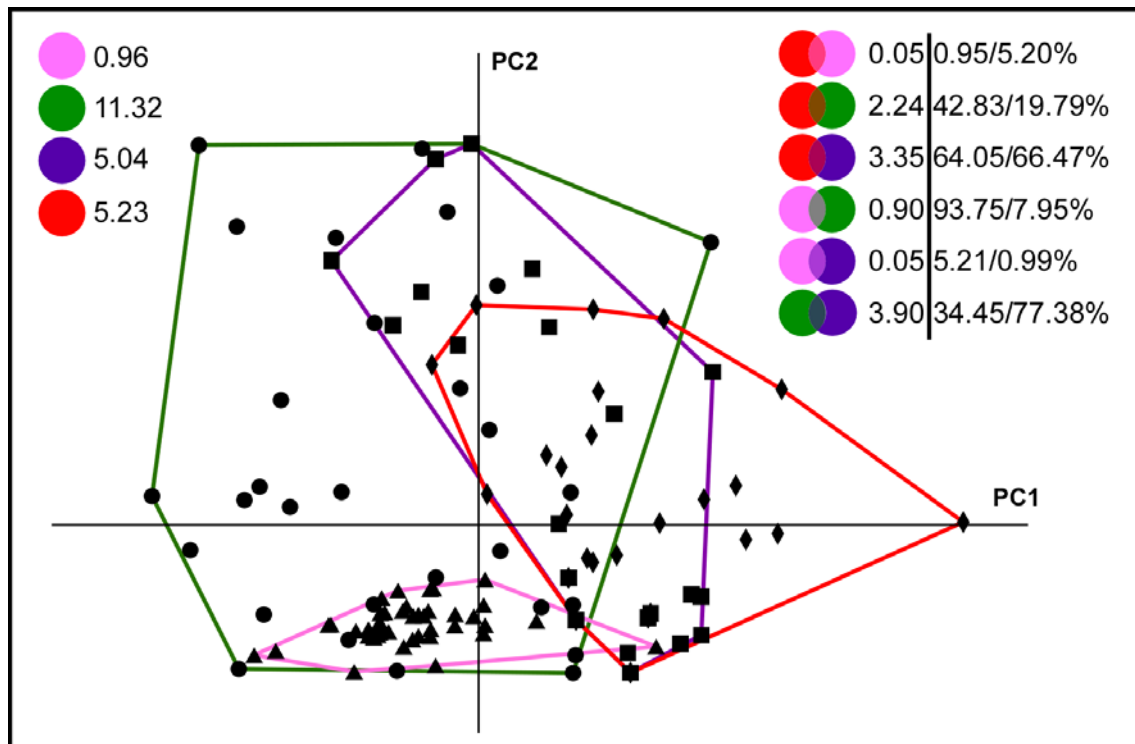


Figure 3. Realized niches of the four hormogastrid clades obtained in the spatial PCA analysis. The points from each clade are shown as follows: Central Iberia - triangles, Eastern Iberia - circles, Disjunct - squares, Tyrrhenian - diamonds. The areas of the realized niches are shown in the top left corner, and the overlap between them (in absolute value and percentage of their respective area) in the top right corner. Central Iberian clade: pink; Northeastern Iberian clade: green; Tyrrhenian clade: red; Disjunct clade: purple.





# Supplementary Material 1

Clade	Latitude	Longitude	Species	Source
Central Iberia	40,480 6	-3,2425	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,430 6	-3,9250	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,827 2	-3,4219	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,739 4	-3,5647	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,519 7	-3,7950	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,597 5	-3,4117	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,856 9	-3,6217	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,947 5	-3,6211	<i>Hormogaster elisae</i> species complex	Novo et al. 2010
Central Iberia	40,939 2	-3,5939	<i>Hormogaster elisae</i> species complex	Novo et al. 2010

Central Iberia	40,510 0	-3,5331	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	40,812 8	-3,6017	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	41,386 4	-3,4283	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,344 7	-4,0133	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	41,185 0	-3,6186	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	40,775 0	-3,7783	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	40,612 8	-3,6781	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	40,801 9	-3,6219	<i>Hormogaster elisae</i> species complex	Novo <i>et al.</i> 2010
Central Iberia	41,298 3	-2,8683	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	41,052 2	-4,1000	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,542 2	-3,6844	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	41,025 0	-2,9928	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,822 2	-3,6492	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,944 4	-3,6447	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,948 1	-3,6947	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,790 3	-3,7081	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,892 8	-4,1331	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,709 7	-3,4367	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,949 2	-3,7631	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,793 1	-3,7461	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,949 2	-3,7303	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,518 9	-3,7622	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,517 5	-3,7514	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014

Central Iberia	40,519 4	-3,7347	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,533 1	-3,7111	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	41,100 8	-3,8128	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,801 7	-3,6906	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,795 3	-3,7028	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,797 2	-3,6997	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,966 1	-3,2531	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,600 0	-3,7714	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	41,364 4	-3,1192	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	41,236 4	-3,7622	<i>Hormogaster elisae</i> species complex	Marchán <i>et al.</i> 2014
Central Iberia	40,945 3	-3,7203	<i>Hormogaster elisae</i> species complex	New
Central Iberia	40,950 7	-3,7103	<i>Hormogaster elisae</i> species complex	New
Northeastern Iberia	42,439 4	-2,8385	<i>Hormogaster riojana</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	41,851 3	1,3279	<i>Hormogaster arenicola</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	41,801 4	2,3477	<i>Hormogaster catalaunensis</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	40,456 4	0,2831	<i>Hormogaster</i> sp	Novo <i>et al.</i> 2011
Northeastern Iberia	42,169 9	0,3315	<i>Hormogaster eserana</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	42,118 0	-0,2485	<i>Hormogaster huescana</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	42,390 6	-0,3725	<i>Hormogaster pretiosiformis</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	42,028 7	1,7121	<i>Hormogaster sylvestris</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	42,585 2	-1,8582	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,522 2	-0,4859	<i>Hormogaster oroeli</i>	Novo <i>et al.</i> 2011
Northeastern Iberia	41,989 6	0,9139	<i>Hormogaster pretiosa</i> var.	Novo <i>et al.</i> 2011

Northeastern Iberia	40,563 6	-0,0177	<i>Hormogaster castillana</i>	Novo et al. 2011
Northeastern Iberia	42,225 0	2,2493	<i>Hormogaster abbatissae</i>	Novo et al. 2011
Northeastern Iberia	42,184 8	0,9033	<i>Hormogaster</i> sp	Novo et al. 2011
Northeastern Iberia	42,231 9	-2,6264	<i>Hormogaster ireguana</i>	Novo et al. 2011
Northeastern Iberia	39,827 6	-0,2612	<i>Hormogaster pretiosa arrufati</i>	Novo et al. 2011
Northeastern Iberia	41,244 2	0,5538	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,050 3	2,8683	<i>Hormogaster</i> sp	New
Northeastern Iberia	41,870 3	2,1162	<i>Hormogaster</i> sp	New
Northeastern Iberia	40,797 0	0,4550	<i>Hormogaster</i> sp	New
Northeastern Iberia	41,971 2	2,6759	<i>Hormogaster</i> sp	New
Northeastern Iberia	41,619 8	2,5731	<i>Hormogaster</i> sp	New
Northeastern Iberia	41,415 0	2,0978	<i>Hormogaster</i> sp	New
Northeastern Iberia	41,130 7	-0,0028	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,468 9	3,1523	<i>Hormogaster gallica</i>	Novo et al. 2011
Northeastern Iberia	43,038 7	2,9479	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,757 3	2,8863	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,880 2	2,1700	<i>Hormogaster pretiosa nigra</i>	Novo et al. 2011
Northeastern Iberia	41,974 1	2,6708	<i>Hormogaster</i> sp	New
Northeastern Iberia	42,205 6	0,9365	<i>Hormogaster</i> sp	New
Disjunct	41,390 9	1,8276	<i>Hormogaster najaformis</i>	Novo et al. 2011
Disjunct	41,807 6	2,0490	<i>Hormogaster</i> sp	New
Disjunct	41,413 9	1,5903	<i>Hormogaster</i> sp	New
Disjunct	41,317 7	1,7174	<i>Hormogaster</i> sp	New

Disjunct	41,221 2	1,2170	<i>Hormogaster</i> sp	New
Disjunct	39,236 5	8,5553	<i>Hormogaster pretiosa</i>	Novo et al. 2014
Disjunct	38,955 8	8,7534	<i>Hormogaster pretiosa</i>	Novo et al. 2014
Disjunct	39,258 3	8,6715	<i>Hormogaster pretiosa</i>	Novo et al. 2011
Disjunct	39,556 5	8,9717	<i>Hormogaster pretiosa</i>	Novo et al. 2014
Disjunct	39,728 1	8,9412	<i>Hormogaster pretiosa</i>	Novo et al. 2014
Disjunct	41,558 9	2,1998	<i>Hormogaster</i> sp	New
Disjunct	41,974 1	2,6708	<i>Hormogaster regina</i>	New
Disjunct	41,184 9	1,4515	<i>Hormogaster</i> sp	New
Disjunct	41,685 3	1,8130	<i>Hormogaster</i> sp	New
Disjunct	41,974 7	2,6933	<i>Hormogaster regina</i>	Rota et al. 2016
Disjunct	39,884 2	8,7880	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Disjunct	39,742 6	9,0214	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Disjunct	39,708 4	8,9719	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Disjunct	39,552 3	9,0767	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Disjunct	39,453 6	9,0101	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Disjunct	39,227 5	8,5442	<i>Hormogaster pretiosa</i>	Rota et al. 2016
Eastern Mediterranean	39,556 5	8,9717	<i>Hormogaster redii</i>	Novo et al. 2014
Eastern Mediterranean	39,728 1	8,9412	<i>Hormogaster redii</i>	Novo et al. 2014
Eastern Mediterranean	36,912 4	7,6739	<i>Hormogaster redii</i>	Novo et al. 2014
Eastern Mediterranean	39,323 3	8,5216	<i>Hormogaster redii</i>	Novo et al. 2011
Eastern Mediterranean	39,406 9	9,2079	<i>Hormogaster redii</i>	Novo et al. 2014
Eastern Mediterranean	39,413 8	9,2148	<i>Hormogaster redii</i>	Novo et al. 2014

Eastern Mediterranean	40,116 3	8,8648	<i>Hormogaster reddii</i>	Novo et al. 2011
Eastern Mediterranean	40,308 8	9,1793	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	40,600 0	8,2991	<i>Hormogaster reddii</i>	Novo et al. 2011
Eastern Mediterranean	40,784 4	8,3872	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	40,878 2	9,0470	<i>H. reddii</i> + <i>H. samnitica</i>	Novo et al. 2014
Eastern Mediterranean	40,770 8	9,6542	<i>H. reddii</i> + <i>H. samnitica</i>	Novo et al. 2014
Eastern Mediterranean	40,892 6	9,5978	<i>Hormogaster samnitica</i>	Novo et al. 2014
Eastern Mediterranean	40,905 5	9,3842	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	40,948 4	9,4988	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	41,027 3	9,5293	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	41,472 0	9,1052	<i>Hormogaster samnitica lirapora</i>	Novo et al. 2011
Eastern Mediterranean	42,516 0	9,3482	<i>Hormogaster reddii insularis</i>	Novo et al. 2011
Eastern Mediterranean	42,804 0	10,4039	<i>Hormogaster samnitica</i>	Novo et al. 2014
Eastern Mediterranean	42,783 4	11,2228	<i>Hormogaster samnitica</i>	Novo et al. 2014
Eastern Mediterranean	43,356 6	10,7195	<i>Hormogaster samnitica</i>	Novo et al. 2014
Eastern Mediterranean	43,333 6	10,5473	<i>Hormogaster samnitica</i>	Novo et al. 2014
Eastern Mediterranean	37,877 3	12,5181	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	37,607 2	13,0291	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	37,316 5	13,6059	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	37,868 9	15,1205	<i>Hormogaster reddii</i>	Novo et al. 2014
Eastern Mediterranean	39,708 4	8,9719	<i>Hormogaster reddii</i>	Rota et al. 2016
Eastern Mediterranean	39,552 3	9,0767	<i>Hormogaster reddii</i>	Rota et al. 2016
Eastern Mediterranean	39,453 6	9,0101	<i>Hormogaster reddii</i>	Rota et al. 2016

## Supplementary material 2

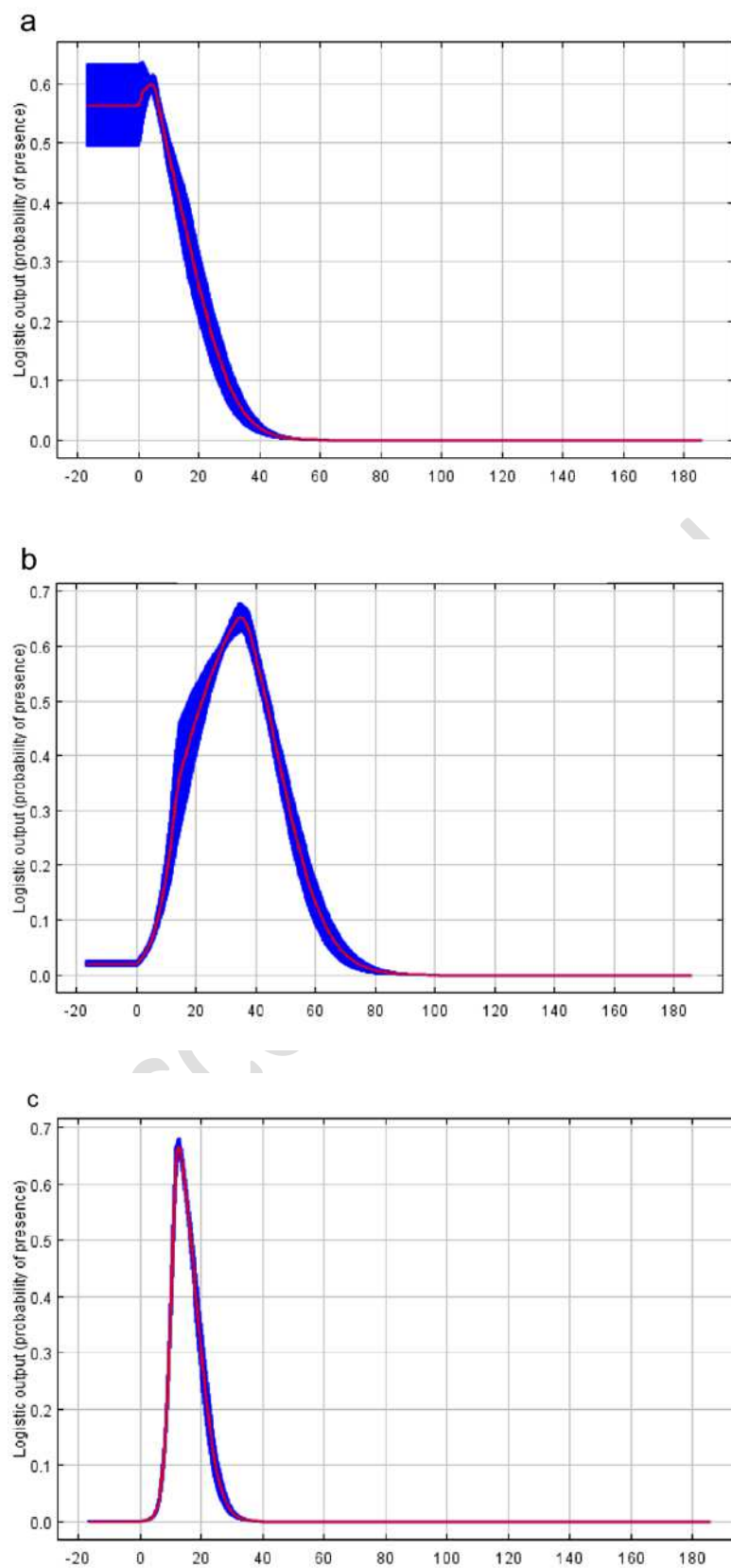


Figure 1. Response curves of the variable Precipitation of the Driest Month (PRDRY) from the Ecological Niche Models of a) Tyrrhenian clade b) Northeastern Iberian clade c) Central Iberia clade. Probability of presence above 0.5 is greater than explained by random, meaning the associated values of the variable are favorable to the presence of the clade. The curves show the mean response of the 10 replicate Maxent runs (red) and the mean  $\pm$  one standard deviation (blue).

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